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How additive manufacturing allows products to absorb variety in use: empirical evidence from the defensive industry

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Abstract

The operations and supply chain management the normative assumption holds that a product's structural and functional elements are fixed pre-production to support efficiency of operations. Firms moving from manufacturing to service are faced with delivering resource for customers in context and absorbing variety in use provides them with a number of challenges. This paper examines AM as a technology that efficiently provides high variety that meets emergent user demand. A single case study is undertaken, drawing upon design change data and in-depth interviews with industry experts. Findings show that in non-digitised environments, introducing design changes to modular products through life creates complexity, where complexity refers to increasing interdependencies between components in the product architecture that lead to increased coordination costs between internal and external supply chains. We find that advances in AM can act as a supply chain solution, managing complexity and allowing products and supply chains to efficiently and effectively adapt close to context of use. Findings suggest that existing theory must expand beyond the normative assumption that the physical product is fixed and the intangible service elements adapt to absorb variety, to include cases where the tangible product can absorb variety to meet emergent need.

Keywords: servitization; variability; modularity, additive manufacturing; supply chain management

1. Introduction

With revenue streams and profit margins eroding, manufacturing firms have shifted from selling product to selling service (Baines et al, 2009; Lightfoot et al, 2013) in order to create new longitudinal revenue streams throughout the product life cycle (Baines et al, 2009; Bustinza et al, 2015). Embodied in this transition toward more outcome-based services is the transition of engagement with the customer from a value-in-exchange to value-in-use relationship (Green et al, 2017). In making this transition, complexity is introduced in the service delivery systems and the processes to support customers use (Neely et al, 2011). Following Simon (1996) and Anderson (1999), we define complexity as non-simple interactions between interdependent resources within a complex system, where a complex system is one made up of a number of interdependent parts which, when combined, make up the whole. The greater variability in customer requirements during the use of the physical product, often referred to as contextual variety, creates greater uncertainty in the design and delivery of servitized offerings (Smith et al, 2014; Batista et al, 2017). In the early stages of research, this uncertainty in demand led scholars to question the scalability of advanced service contracts, such as outcome-based contracts (Ng et al, 2009; Visnjic et al, 2017; Batista et al, 2017), given each contract was deliverable like a 'project' (Hobday, 2000; Salonen, 2011). Advances in digital technologies as part of industry 4.0 have mitigated some of these challenges, bringing increased automation and rapid communication that allow advanced services to be scaled across contracts (Oesterreich and Teuteberg, 2016). Industry 4.0 technologies, in particular the IoT and Big Data Analytics, reduce the information asymmetry between provider and customer use (Grubic, 2014; 2018; Baines & Lightfoot, 2013; Opresnik & Taisch, 2015; Schroeder et al, 2019). Big data and data analytics are now a key resource for servitized manufacturers (Schroeder et al, 2019), enabling organisations to monitor use and the operational condition of products situated in the customers' context (Ben-Daya et al, 2017; Rymaszewska, et al, 2017; Grubic, 2018).

Whilst technology has improved efficiency, supported scalability in the delivery of advanced services and supported digitally enhanced servitized supply chains (Johnson & Mena, 2008; Vendrell-Herrero et al, 2017; Xu et al, 2018), research investigating product manufacturing supply chains in servitized contexts is limited. This is reflected in Green et al.'s (2017) thematic analysis of the academic literature that finds the main focus of research for servitizing manufacturers has been the intangible service offerings and their design. Focussing only on the intangible service elements appears counter intuitive.

given servitization is often described as product-centric (Baines et al, 2009) and the product is best placed to absorb contextual variety given it resides within the customers' context of use (Smith et al, 2014). We argue that there are two main reasons for this. First, research has historically assumed product use is stable and predictable in advance of production. The manufacturing theories developed in closed system environments can be transferred to servitized settings. A second assumption follows the normative view that the product is a relatively fixed object (Kimbell, 2011), with little consideration given to product adaptation in use and in context (Ng, 2013).

Scholars have challenged this viewpoint. For example, Ng et al. (2009), Ng et al. (2012) and Maglio et al. (2015) questioning whether simple extensions of existing engineering, supply chain and operations models are applicable within servitized contexts or human-centred service systems. They asked whether new ways of thinking about design may be required, with emphasis placed on value in use, technology, resource integration, emergence and contextual variety. In the context of advanced services, Smith et al (2014) challenge existing paradigms within servitization and suggest the design and production of the physical asset, as part of the service delivery system, in advanced services needs further investigation as both customer in context and the supply chain may interact with the physical asset through life. The key design challenge for the physical product and manufacturing supply chains within servitization therefore arises from customer-induced variety that emerges during the use of the asset (Ng & Briscoe, 2012; Green et al, 2017; Zou et al, 2018). Godsiff (2010) label these as 'unknowns' and describe them as a fourth category of customer requirement, in addition to runners, repeaters and strangers (Parnaby (1988), that is not known in advance of use but could be feasible to satisfy.

Matching variety created by unknowns achieved through the re-configuration of the physical asset (variety matching variety) does not align with existing manufacturing theory for three reasons. First, these reconfigurations may take place on an individual customer basis and therefore may not be a scalable or feasible solution for product-centric servitization (Ng & Briscoe, 2012; Green et al, 2017). Second, traditional manufacturing supply chains may not be able to respond to customer change in an efficient manner i.e., responding within hours, day or weeks when the need arises (Holmström & Partenan, 2014). Third, whilst numerous authors (e.g., Cenamor et al., 2017, Salonen et al., 2018, Rajala et al., 2019) suggest modularity theory developed in the manufacturing domain is a suitable strategy for matching the diverse needs of customers for servitized manufacturers, the literature would suggest it is not always the case. This is because the modularity requires the complete functional and structural attributes of modules to be specified and frozen in advance of production of the physical asset (Simon, 1996; Baldwin & Clark, 2000; Henfridsson et al, 2014). Whilst they did not investigate the effect of servitization on the design of the asset, Spring & Araujo (2017) recognise that once designed and produced, a modular product is still a fixed bundle of functionality. Should any unknowns emerge during the use of the asset, it may not be possible to integrate the required functionality (design change) in an efficient and effective manner. Given the opportunity for re-design is significantly reduced when the design is transferred from design to production (Henfridsson et al, 2014), there is the potential that any design change that is integrated could lead to increased complexity within the products architecture. Complexity in this context refers to a higher degree of interdependence between components within the system such that a change in one component requires changes to another i.e., the architecture is integral (Ulrich, 1995; Baldwin & Clark, 2000). This means required design changes to satisfy use may fall outside the boundary of the existing architecture and diminish the degree of modularity within the existing architecture. According to the literature, should an architecture move from modular to integral (tight coupling between modules), then we would expect to see increasing coordination costs between internal and external supply chain partners (Baldwin & Clark, 2000; Mikkola, 2006).

Advances in additive manufacturing technology (AM), allowing for much greater variety and rapid adaptability of a product, have led scholars to believe the application of AM could meet the potential challenges discussed above (Ng, 2013; Holmström & Partenan, 2014; Lyly-Yrjänäinen et al, 2016). Responsive product service systems (PSS) built around AM technologies that are able to rapidly integrate new functionality in the physical product to meet emergent customer demand is therefore an area of that warrants further research (Holmström & Partenan, 2014; Lyly-Yrjänäinen et al, 2016). There are also calls for further research from practice. The Centre for Defence Enterprise (Gov, 2014) called for further research as to whether AM can be used to rapidly build, modify and adapt bespoke military equipment at the point of use. Deloitte (2014) have identified AM as a technology that could innovate supply chains to support product evolution, including customisation to individual customer requirements and responsiveness to desired changes. Finally, AM is widely used by a range of industrial manufacturers and service providers including Rolls Royce and General Electric (Sutherland, 2019).

Having identified a gap within the literature, the objective of this research is two-fold. First, we investigate how adapting products to satisfy the variability in the customers' use context increases complexity (interdependence between components of the system) for both the physical product and its associated supply chains. Second, we explore whether advances in AM can mitigate some of these challenges and allow organisations to manage complexity and scale AM across contracts. To address the knowledge gaps, the research addresses the following research questions:

1) Does servitization introduce complexity in a) the design and production of the physical asset and b) the supply chain that supports the physical asset?
2) Can additive manufacturing allow organisations to support products in use without increasing complexity of the physical product and its associated supply chains?

The article is structured as follows. First, we provide a research background focussing on the challenges of dynamic requirements in high variety, servitized contexts. Second, we examine how AM could overcome some of the potential challenges. We then introduce the methodology before presenting the results. Finally, we present the discussion and conclude with theoretical and practical implications, limitations and future research opportunities.

2. Background

2.1 Servitization, dynamic requirements and challenges to existing approaches

Traditionally, operations and supply chain management [O&SCM] has developed theories for design and production in closed system environments that treat the customer as exogenous to the system (Godsiff, 2010). This allows organisations to optimise their processes and achieve efficiency as it reduces the amount of variety within the system that could be introduced by the customer. Traditional O&SCM thought states that variety should be treated as a disturbance introduced by the customer and that they should separate design and context to minimise this disturbance and maximise efficiency of the technical core (Ng et al, 2009; Godsiff, 2010; Godsiff et al, 2018). Given the need to reduce variety disturbing the efficiency of the system, organisations focus on developing rigid specifications of user requirements and performance attributes early in the design cycle (Garud et al., 2008; Ng et al., 2009). This approach aligned with the scientific approach to design outlined by Simon (1996). Within the literature, a requirement of modular design is that a complete picture of the structural and functional elements of the product are developed early in the design phase. This is so that they can be frozen into the product architecture prior to release to the production team (Henfridsson et al, 2014). Freezing specifies that clear boundaries, a fixed specification and stable outcomes in use are a prerequisite of modularity and design more broadly (Garud et al, 2008), pushing the O&SCM agenda to separate design and context and assume stable products and processes (Hayes, 2002).

The separation of design and context within modularity is captured by Langlois and Cosgel (1998) who, referring to propositions by Pareto, have said '*we do not need the consumer to be present at all so long as he leaves us a snapshot of his preferences*' (p.107). Creating this snapshot allowed organisations to freeze the user requirements so that they can inform a complete description of the structural and functional elements of the product architecture in advance of production. Specifying the complete description of the architecture during the design phase leads to a separation between design and context, and to organisations separating design and production activities. Separating these two activities allows organisations to create flexibility in design (Ulrich, 1995; MacCormack et al, 2001), economies of scale in production (Salvador, 2007) and the opportunity to leverage external organisations manufacturing capabilities within the supply chain (Fixson, 2005; Langlois, 2006). Traditional O&SCM theory that worked off of the basis that organisation's do separate design and context then focused on improving efficiency through optimisation of the delivery system in a closed system environment (Ng et al, 2009; Batista et al, 2017). Research until now has therefore focussed on the optimisation of the design and production of the asset and the supply chains supporting its creation and delivery up until the point of exchange.

In servitized environments separation is difficult to achieve as design and context become intimately entangled due to a shift from value-in-exchange to value-in-use embedded in contracts (Smith et al, 2014; Green et al, 2017). Zou et al (2018) state that a challenge for manufacturers in the transition from product to service is the heterogenous customer requirements that emerge in the product use phase that introduce variability into the system. Kimbell (2011) highlights that what happens after the point of exchange was not of interest to product organisations as they bear little to no responsibility for the product in use. Whilst product change can happen independently of servitization, product use in context becomes increasingly important in service contracts. This is particularly evident where firms have responsibility to deliver resources for the end user to achieve their goals. Thus, servitization embodies the entanglement of design and context and requires organisations to acknowledge responsibility for product change. Providers able to absorb variety in the customers' use contexts can deliver and support advanced services such as availability, performance or outcome based contracting (Smith et al, 2014).

In shifting from a closed system to an open system, an organisation is unable to separate and shield its technical core from customer induced variety as design and context become intimately entangled (Ng et al., 2009; Green et al, 2017). This poses a number of challenges for organisations relying on existing manufacturing theories that require functional and structural attributes to be frozen in advance of use. Customer requirements may be unknown prior to use (Godsiff, 2010) and the window for re-design is limited once the specification has been frozen and transferred to the production unit (Henfriddson et al, 2014). In demanding a complete specification of functional and structural elements prior to production, the organisation assumes a low variety of use (Green et al, 2017), but research in servitization shows that use is rarely low in variety and may require functionality that was not originally designed into the asset (Ng et al., 2009; Ng & Briscoe, 2012; Smith et al., 2014; Green et al., 2017; Batista et al., 2017). In the context of supply chain management, Parry et al. (2016) label this 'patterns of use'.

Organisations must study patterns of use and absorb variety via reconfiguration of the physical asset. They may struggle to manage complexity within the existing architecture of the product and supply chain because the entanglement of design and context may reduce flexibility in design, diminish their ability to achieve economies of scale in production, as they need to serve individuals, and the speed at which resources are required may limit their ability to leverage other organisations manufacturing capabilities within their supply chains. Thus, servitization becomes difficult to scale because each contract becomes a 'project' if organisations seek to serve individuals via product reconfiguration using existing manufacturing theories and technologies. This assumption corroborates with earlier work by Ng et al. (2012) and more recent work by Maglio et al. (2015) who question whether simple extensions of existing engineering, supply chain and operations models are applicable within servitized contexts or human-centred service systems.

2.2 Digital disruption and complexity management with additive manufacturing

AM is an industry 4.0 technology that produces physical components from a digital file by 'printing' the component layer by layer (Wagner & Walton, 2016). It has a number of benefits in that it can support local production (Wagner & Walton, 2016), the reduction of inventory, and therefore costs, by storing components digitally (Liu et al, 2013) and on-demand production (Srei et al., 2016). Maull et al. (2015) argue AM is able to satisfy the demand side of a 'full pull' economy and compliments traditional manufacturing in low volume high variety contexts (Holmström et al, 2016). AM implications for supply chains include closer to the customer production (Cohen et al., 2014), shorter, simpler supply chains (Gebler et al., 2014) and provides a new source of competitive advantage for supply chain management (Zhong et al., 2016). AM has potential as a digital technology to unlock opportunities across the supply chain from design to production to use (Chan & Jumar, 2014; Tziantopoulas et al., 2019). AM will likely result in shorter supply chains and act a key technology for servitization (Dinges et al., 2015) and hybrid solutions of AM and traditional manufacturing within both design and the supply chains that allow products to be adapted in use, with what are call 'product instances' (Holmström & Partenan, 2014). Khajavi et al (2013) found AM offers shorter production times meaning distributed supply chains becomes a viable option for OEMs. Liu et al (2014) found that AM could act as a supply chain solution, reducing the required inventory for aircraft spare parts. Finally, Li et al (2016) found that AM has superior sustainability benefits compared with traditional manufacturing supply chains and will likely bring economic benefits. The literature provides evidence that AM acts as a supply chain solution.

AM is feasible for small and medium lot sizes and has been shown to have economies of scale in production of one unit (Petrick & Simpson, 2013; Huang et al., 2013). The lack of tooling means each part within a print bed can be unique (individual), meaning customisation is less restricted as it is driven by software as opposed to tooling, resulting in greater freedom in the production of unique parts (Holmström et al, 2010; Petrick & Simpson, 2013). As AM requires no tooling, virtual parts can be stored in digital format closer to the point of use, until needed by the customer. As the technology allows a delayed binding of form and function and does not require tooling that is expensive to produce, the final output does not have to be fully specified early in the production cycle. Yoo (2013) describes this as delayed 'function binding'. Within AM, function binding still requires the functional and structural elements to be defined in advance of production and use. However, the point at which this binding takes place can be delayed until the requirement emerges from variability in use. This allows components to be product agnostic as opposed to specific, giving organisations the ability to draw on multiple design hierarchies to modify a product as opposed to the single design hierarchy it is bound to (Yoo, 2013). For example, software driven changes can be implemented based on information provided by the operator of the machine, allowing a specific, pre-designed blueprint to be modified based on the parameters entered into the software. Parameters allow variety but are bound to maintain modularity and component integrity.

AM therefore allows for the product to be temporarily complete when a particular configuration of resources is required for outcomes in use (Yoo & Euchner, 2015). The design freedom associated with AM could potentially mitigate some of the architectural complexity that may arise in the use of traditional manufacturing. AM provides greater flexibility in drawing on components from different design hierarchies and producing these in small lot sizes at a more efficient pace than traditional manufacturing supply chains. AM can act a supply chain solution within a servitized context (Holmström & Partenan, 2014; Green et al, 2017). Whilst it is anticipated in most industries the majority of a product will be produced via traditional technology (a standardised platform) where form and function are bound prior to production, AM could compliment this through the production of individualised components for specific customers' (variety and customisation at the point of use) (Holmström & Partenan, 2014). Parts can be designed and implemented late, and in response to unknowns that emerge in the customers' use of the product. AM technology affords the ability to extend design flexibility through life whilst retaining scale economies in a way that was not achievable with traditional manufacturing (Holmström & Partenan, 2014; Lyly-Yrjänäinen et al, 2016). AM affords urgency in terms of speed of change, greater flexibility in terms of what can be produced and is feasible on an individual basis. AM is a digital manufacturing process that is transforming manufacturing supply, much like digital did to phones, video and music (Ihl & Piller, 2016). However, these authors did not address whether AM can support product reconfiguration in use without increasing complexity in the product and supply chains.

However, whilst seen as a potential solution to many existing manufacturing supply chain problems (Liu et al, 2013; Tziantopoulos et al, 2019), the technology still has technical and feasible constraints that need to be overcome. For example, whilst often described as a rapid production method, post-production finishing and treatment times aligns with traditional methods, material options remain limited and the throughput rate of printed parts is slower than traditional manufacturing (Berman, 2012; Weller et al, 2015). Furthermore, design changes are most likely to be made to smaller metal or plastic components due to limitations in AM production capabilities. For example, in a case study, Heinon & Hoberg (2019) found that in their dataset of 53,457 parts, only 8% of stock keeping units and 2% of total units could be produced via AM. Capability is not the only constraint to the successful exploitation of AM technologies. For example, Walther (2015) highlights the need to reassess security aspects in digitised production environments and Srai et al., (2016) identify significant regulatory and certification challenges for AM where appropriate quality assurance processes are lacking compared to traditional manufacture. This is particularly important for areas such as aerospace and defence where component approval is often determined by an external source (e.g., the Federal Aviation Administration) given the environments the safety critical environments organisations operate within.

Based on our review, whilst AM has some limitations in its current form, the literature suggests AM can manage product and supply chain complexity introduced by variability in the products use because of the flexibility it offers compared with traditional manufacturing. However little empirical evidence exists in literature to support these claims. Testing assumptions and empirical evidence of AM’s ability to address O&SCM issues in the transition from product to service provision is the basis of this study and contributes to continuing calls to empirically investigate O&SCM challenges in these contexts (Oliva & Kallenberg, 2003; Smith et al, 2014).

3. Research Design and Methodology

3.1 Case Study

Case studies as a research strategy for investigating complex phenomena and gaining a detailed understanding (Eisenhardt, 1989). Case studies are useful when (1) the phenomenon is difficult to separate out from its natural setting (Benbasat et al, 1987; Yin, 2003) and (2) the phenomenon being investigated is still in the exploratory phase of research (Meredith, 1998). Little research has been conducted into to product complexity in servitized contexts and AM as a digital technology to support innovation. Based on these beneficial attributes of case study research and given this studies purpose, a single case study is deemed suitable for this research.

3.2 Case Selection

There are specific requirements for case selection e.g., the organisation is involved in services/servitization, the customer is using the physical asset in a high variety context, design changes that extended beyond the scope of the initial architecture are made through life, the organisation is using or seeking to use AM for service provision etc. It is therefore important that a case is selected where the phenomenon are transferable observable (Patton, 1989). Based on these requirements, the case selected is from the defence industry, where design changes are made to physical assets through life on a regular basis, especially during wartime. The case organisation was developing its AM strategy within the context of product-centric servitization where their offerings are subject to high variety. The case organisation is one of BAE Systems Plc subsidiaries that designs, manufactures and supports a vast product range of land combat vehicles through life. Whilst most of the through life support activities focus on the spares and repairs activities, during wartime, the organisation is subject to a number of design change requests from the customer. Within the defence industry these are called Urgent Operation Requirement (UOR) and are defined as: *'Requirements for military or sensitive security goods arising from:*

a. *The identification of previously un-provisioned and emerging capability gaps because of current or imminent operations* (The Defence and Security Public Contracts Regulations, 2011, pp.1).

A UOR is often an 'unknown' (Godsiff, 2010) that emerges during the use of the physical asset and therefore requires new functionality to be integrated to satisfy customer requirements in use. The UOR process within the defence industry satisfies the requirements of this study as the organisation provides through life design services, the vehicles were in use in high variety contexts, the organisation was developing its AM strategy within the context of servitization and that the provision of UORs meant that design changes that extend beyond the scope of the initial architecture were made throughout the life of the physical asset.

3.3 Dataset

The first part of the research focussed on architectural complexity in the context of servitization and required access to the company's vehicle architectures over time. This was provided between the year 2001-2014, spanning the period when the UK was actively involved in two military campaigns in Iraq and Afghanistan. Within these two campaigns, the vehicles were subjected to a number of UORs (n=60) across all vehicle platforms within the sample (n=5). Therefore, each vehicle had, on average, 12 design changes. The research was able to record the changes to the vehicle architecture each time a UOR (design change) was completed. From the literature review, we identify servitization as a driver for product change as in service the provider takes greater responsibility for the performance of the product in use. Neely (2008) recognises UORs as a 'design and development' category of servitization for product orientated product-service systems. In product-oriented PSS the product is transferred to the customer and additional services related to the product are provided e.g. design and development services. Design changes are instigated and paid for by the customer. In use-oriented PSS the product may be retained by the provider, and as the provider is often responsible for use performance, they also may instigate design change and could now be responsible for the cost of product change.

In addition to the secondary data on vehicles architecture, documents included engineering standards, MoD publications and media articles related to the subject. Primary data was collected from thirty interview respondents from different functional disciplines to provide detailed insight into a) the complexity that arises within the context of the physical product and b) the potential benefits of AM in managing or mitigating some of this complexity. The broad spectrum of respondents (table 1) helped to avoid subjectivity and bias (Eisenhardt and Graebner, 2007). The interviews were conducted over two stages. The first round of interviews (n=22) were conducted concurrently with the development of the DSMs to discuss AM, UORs, engineering challenges, supply chain challenges and opportunities. Following the completion of the DSMs, the second round of interviews (n=8) with more senior members of staff focussed on similar themes but included the results of the DSMs allowing for discussion of the challenges that led to changes in the products architecture. Coding of the first round of interviews highlighted a need for greater insight into emergent themes of urgency, emergence and design change novelty from participants in the second round, see table 1.

Participant Position	**Number of Interviewees**
First Round of Interviews	
Engineering Staff	17
Service Representatives	5
Second Round of Interviews	
Technology Lead	1
Head of Availability Services	1
Technical Programme Manager	1
Platform Managers (of the three vehicles studies)	3
Field Service Representative Manager	1
Strategy Executive and Principle Technologist	1

Table 1. Interviewee information.

Further primary data was collected during discussions, vehicle tours and ad hoc meetings with staff. These were recorded as field notes were typed up for analysis immediately to maximise recall.

3.4 Analysis

According to the literature "*modularity is a structural fact: its existence can be determined by inspecting the structure of a particular thing. If the structure has the form of a nested hierarchy, is built on units that are highly interconnect in themselves, but largely independent of other units; if the whole system functions in a coordinated way, and each unit has a well-defined role in the system, then by our definition, the thing is modular"* (Baldwin & Clark, 2000: 132). This view indicates there is more than one type of architectural configuration. This aligns with the extant literature where architectures are often described as being either modular or integral (Ulrich, 1995). The latter characterised as having tight coupling between modules (i.e., they are interdependent within and between) and greater coordination costs between internal and external supply chains as changes to one subsystem require changes to another, interdependent module (Ulrich, 1995; Baldwin & Clark, 2000). Coordination refers to the degree of communication and collaboration between members of the system developing and producing a module. Modularity reduces coordination challenges and therefore costs, as the architecture, interfaces and standards have been defined a priori, allowing members to support one another with little to no communication (Baldwin, 2008). Within this case study, the vehicles studied are designed as modular against the original specification. This is reflected in the design structure matrix (DSM) of each vehicle before any design changes take place.

Observing the structure of a vehicle's architecture overtime will determine whether or not the vehicles architecture remains modular i.e., does the degree of coupling between modules increase over time with each design change that is implemented. The structure of the architecture is examined from the perspective of interactions within and between modules and the relative change in these to give an indication of the degree of coupling between modules. In line with the literature, should interactions increase between modules then the degree of modularity present within the architecture will have diminished. This is because the degree of coupling between modules will have increased.

This can be seen as a proxy measure for complexity within the product architecture and the products (Baldwin & Clark, 2000). Interviews identified if changes to product architecture had implications for the supply chain. From literature, we expect to see increased supplier coordination costs if the degree of modularity in the vehicles diminishes i.e., modules become more tightly coupled (Baldwin & Clark, 2000; Mikkola, 2006; Baldwin, 2008).

To conduct this analysis, models for each vehicle architecture were built using the design structure matrix (DSM) tool (Browning, 2001). DSMs are a systems engineering tool used to model product architectures. This tool is suitable for systematically analysing relationships between components within a system, analysing the degree to which a product is modular and visualising the structure of a products architecture (Browning, 2001; Eppinger & Browning, 2012). To construct the models, the following steps were taken:

1) The system is decomposed into its component level;
2) Interdependencies/interactions between the components are identified and mapped within the matrix; and
3) The units are rearranged to show the modules within the architecture (Pimmler and Eppinger, 1994)

To support the development of the DSMs, platform champions (n=3) with detailed knowledge of the vehicles being analysed were identified, one for each of the three vehicle families. Data was provided at a module level for analysis at the subsystem level. This was found to be a suitable level of analysis based on the research background (e.g., Mikkola, 2003) and the case organisation is a prime systems integrator. To construct the DSMs, initial meetings with each platform champion were held, vehicle tours were conducted and the research team was provided with a breakdown of components for each vehicle with the UORs and their date of integration highlighted. Once the initial architecture with no UORs was created using the DSM, it was checked and verified by the platform champions before the subsequent DSMs were created each time a UOR was integrated. The final DSMs were again checked by the platform champions and signed off as correct before analysis took place. The platform champions were also asked to rate the complexity of each design change on a scale of low-medium-high, record whether the changes took place internally or externally to the vehicle and whether the changes were material, electrical or information or a combination of these. With respect to design change complexity, the research follows Vickery et al (2015) who see complexity as the number of elements with a system (this research sees this as each design change), where they assume a higher number of elements is related to greater interdependencies between components and therefore higher complexity. This would allow additional patterns to be observed within the data to provide more detailed insight into the design changes. Following completion of the DSMs, the data contained within the DSMs (i.e., the number of interactions inside modules and the number of interactions outside the modules) was tabulated into a spreadsheet and then used to produce a number of graphs representing the data. This aligns with recommendations by Miles et al (2014) to condense the data into a format that would allow for conclusions to be drawn and verified. Given the DSMs were difficult to interpret at face value, it was important this additional form of data display and analysis was conducted.

The analysis of the DSMs was supplemented with a thematic analysis of semi-structured interviews, documents and field notes. To code the data, we followed the procedure for thematic analysis outlined by Braun & Clark (2006). A single member of the research team coded the transcripts, with coding driven by key concepts from the literature and within scope of the research questions. Text was then extracted into NVIVO where text most relevant to the research questions was retained, following Miles et al (2019) who suggest condensing and displaying data before analysing and verifying conclusions. Text was labelled by theme with all resultant themes in Appendix table i in the appendices. A second researcher reviewed the data and themes to check reliability, and allowing for the flexibility of new and sub themes to emerge during analysis (Braun & Clark, 2006).

Interviews provided additional insight into product and supply chains complexity arising from design changes driven by use, the drivers of this complexity in a servitized context and the use of AM in overcoming complexity in design and production of the physical asset in a high variety context.

4. Results

4.1 Does servitization introduce complexity in a) the design and production of the physical asset and b) the supply chain that supports the physical asset?

In addressing RQ1A, the analysis of the product architectures DSMs found that servitization does introduce complexity into the design and delivery of the physical asset.

As can be seen in table 2 and figure 1, as design changes that extend beyond the scope of the original specification are integrated over time, interactions outside of modules increase at a faster rate than those inside. Interactions outside of modules increasing more than those inside modules highlights that design knowledge related to the implemented changes was not contained within new or existing modules architecture. The data shows the degree of coupling between modules increased and modularity diminished each time a design change took place.

Design change	Interactions inside modules		Interactions outside modules		Change Type Material=M Electrical=E Information= I	Area of Change on the Vehicle Internal = I External = O	Perceived Design Complexity High = H Medium = M Low = L
	before design chang e	after design chang e	before design chang e	after design chang e			
1	104	106	88	90	L	M	O
2	106	106	90	94	M	M,E	O/I
3	106	106	94	98	M	M,E,I	O/I
4	106	112	98	100	L	M	O
5	106	112	98	100	L	M,E,I	O/I
6	112	112	100	138	H	M, E	O/I

Table 2. Tabulated data from the DSM for vehicle A1.

Table 2 presents the cumulative effect of six design changes made to vehicle A1. The data highlights that design changes that are made both internally and externally to the vehicle and those with multiple change types are the most complex to integrate according to the platform managers. Interestingly, they noted that these were largely because of restrictions in the available space, the existing material components within the product and limitations of existing manufacturing technology in terms of what it can produce (geometry), with managers noting that AM could have made some of these changes easier due to flexibility in the design and production of components compared with traditional manufacturing. Design change 5 is was classified as a modular upgrade, as it was upgrading the performance of existing resources on the vehicle and therefore did not change interactions within the vehicle. The interactions before and after are graphically presented in figure 1. The trend shown in figure 1 is that interactions outside of modules gradually increase over time whilst those inside remain relatively stable. The implication of this is tighter coupling between modules and this is reflected in figure 2.

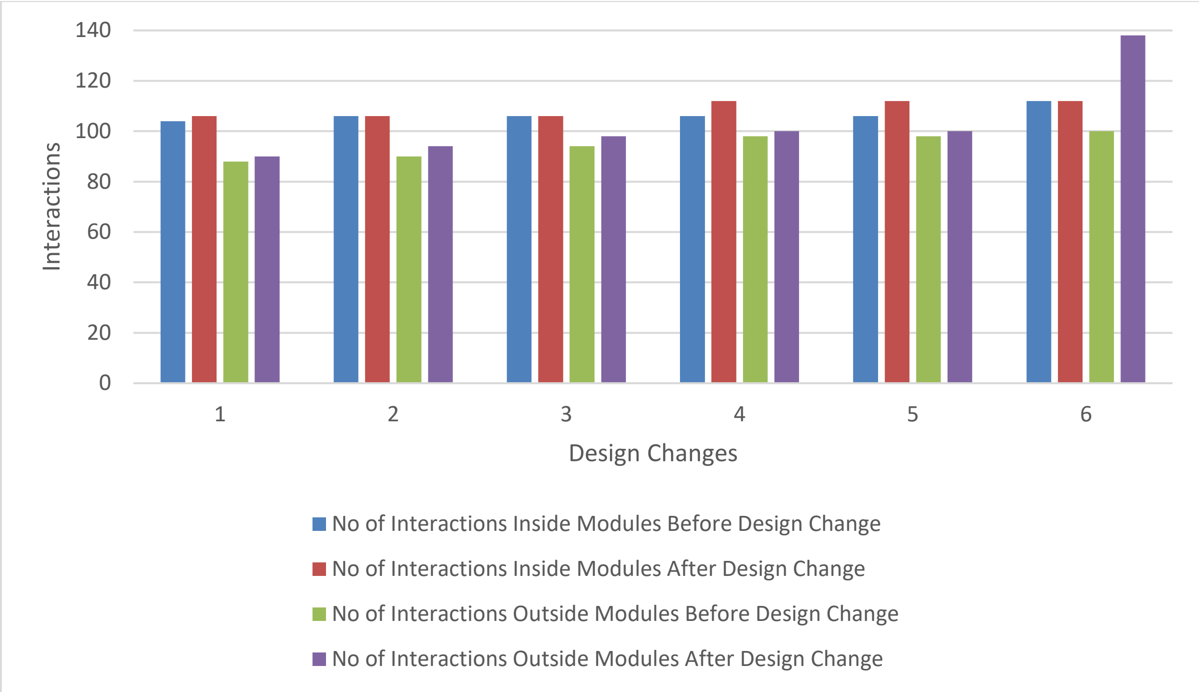
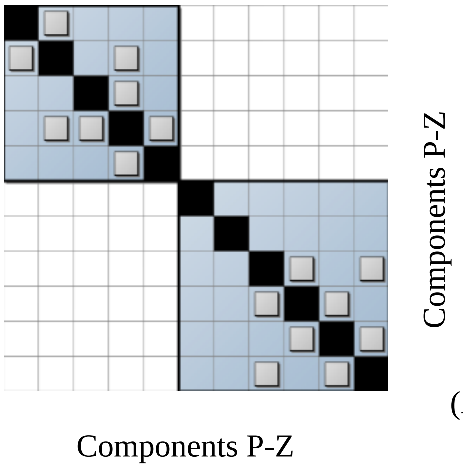
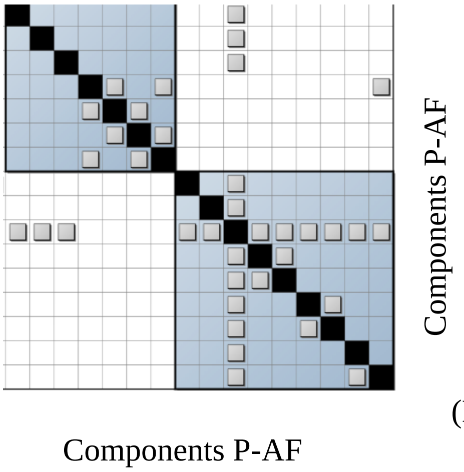


Figure 1. Vehicle A1 interactions pre and post design changes



(A)



(B)

Figure 2. (a) A segment of vehicle A1 DSM pre UORs and (b) the same segment after all UORs for vehicle A1 showing increased interactions outside of existing modules.

Figure 2 highlights a segment of vehicle A1s DSM. Figure 2(a) shows the first DSM with no UORS and figure 2(b) shows the same segment, post all UORs for vehicle A1. These two modules are a mixture of mechanical and electronic components. In line with figure 2 and table 2, we can see an increase in interactions both within and outside of modules. Interactions outside increase more than those inside, highlighting that the degree of coupling between modules is increasing, increasing the dependency between modules within the architecture. This correlates with Vickery et als., (2015) description of complexity. Prior to the design changes, the two modules highlighted did not need to interact with one another. They did interact with the core platform (the vehicles hull and electronic systems) and other modules in the system. However, following the integration of the design changes for vehicle A1, we see that these two modules now interact via a number of components. This highlights a greater degree of coupling. Whilst the modules could previously be individually upgraded and modified independently of one another, the tighter coupling means much greater coordination between module developers is required in subsequent design changes. This trend was found across all platforms studied, and recognised as an issue by the team.

Using the logic of modularity theory, the integration of new components should see interactions contained within module boundaries and only loosely coupled to the rest of the system if they are integrated within the existing design rules (Baldwin & Clark, 2000). From the results of the DSMs we can see that interactions outside of modules increase at a faster rate than those inside of modules, leading to a tighter degree of coupling between modules. This indicates that degree of modularity within the architecture is diminishing, making changes more difficult as change in one module impacts upon another, increasing complexity. A general pattern is observed that interactions outside of modules increase at a faster rate than those inside when the required functionality does not align with the existing architecture. This does not occur for design changes that align with the existing modular design rules as design knowledge (i.e., the modifications made) is kept within the existing modules and interdependencies between components do not extend outside of the module.

From figure 1-2, table 2 and supplementary insights from a platform champion, we see that the seventh design change has the most significant effect on the architecture. As a result, the DSMs indicate that there will be a need for more closely coordinated communication between internal design teams and supply chain partners. This may add to coordination costs and complexity within the supply chain according to the senior members of the case organisation. Traditionally, modularity allows the coordination costs to be reduced as module developers can work independently of one another as they are coordinated by the design rules (Baldwin & Clark, 2000). However, the nature of these design changes (UOR design changes), where modules become more tightly coupled, required greater communication between previously autonomous and independent functions of the internal and external supply chain. For example, designers, engineers and procurement who used to sit independently are now co-located and require additional meetings to coordinate activities, reflecting the need for integrated working. This is reflected in the following quote:

"usually you get people co-located the best we can or at least if we can't co-locate them every morning, down by the wagon usually, have a line side meeting…everyone knows

what the key things are for that particular day and everyone works together as best they can to do that".

Increases in external interactions therefore led to complexity and greater coordination efforts between teams within the organisation. Once the conflict the customer was involved with ended, there was less requirement to meet in the manner they did during times of conflict. A primary reason for this was the customer no longer need 'urgent' changes, meaning the organisation no-longer had to maintain daily coordination efforts. This further supports the second sub theme, discussed below.

In responding to emergent requirements in use and extending the functionality beyond what was anticipated in the original architecture, our results show organisations are unable to retain complexity inside the modules that currently exist within their products, providing evidence that addresses RQ1A and RQ1B. The results presented are consistent across all five vehicles studied.

Based upon our results and the literature, we formulate the following research proposition:

Research Proposition 1: Integrating design changes that increase interdependencies between modules will increase complexity for service providers.

In addition to the DSMs, the thematic analysis supported our initial findings from the products architecture and supplemented them with a greater understanding as to why this complexity arises.

Thematic analysis of the interview data and field notes led to the creation and definition of an overarching theme of 'drivers of complexity'. This theme is defined as '*Factors that drive a system(s) toward a greater degree of complexity with respect to the strength and amount of interdependencies between elements of the whole system'.* Within this theme, a further three sub themes were identified and defined. These were emergence, urgency and novelty of the desired design change. The data to support these themes and definitions of each are now presented.

Within the data, emergence was a recurring theme that kept being described a driver for complexity within the product architecture and the manufacturing supply chain. Emergence in this case is described as the creation of new design requirements from the interaction between new or existing entities within a particular context. Within this case, interactions between the military personal, their vehicles, the physical environment they are operating in and the adversary within which they are engaged in active conflict with. For example, when asked why complexity emerges in the design and production of the physical product an interviewee made reference to an emergent threat to the vehicle that had not been foreseen, was addressed, but introduced complexity stating:

"Storage is a big issue. It sounds trivial but in theatre they had a real problem with water, because they had to drink, what was it?...Something like that, so if you go out for any length of time, three or four day mission, suddenly you've got to store 60 litres of water on a vehicle for a crew of three or something like that, well where's that going to go? Well, we didn't plan that in the design because it wasn't a requirement".

The outcome of larger material design changes, such as those that added significant weight, required changes in key components such as the engine, brakes and suspension. The reason for this was that the additional weight violated some of the performance parameters within the design rules. This triggered a design activity that required new performance parameters to be generated, and therefore design rules, and other modules to be modified and upgraded in order to allow the vehicles to function as required. Adding weight changed the interactions between the modules (e.g., powertrain and subsystems) that altered the contracted performance attributes (e.g., power to weight). Once affected subsystems were modified to account for the additional weight, the system was able to return to its existing state, though any further weight added meant this cycle would be repeated. Violating the design rules, that required them to be re-worked, is a timely and costly activity as it requires new trials and testing.

When discussing the concept of UORs more broadly and the purpose of design changes to support customers' outcomes in context, a member of the service team discussed the philosophy behind them and the role emergence plays in driving design changes:

"The philosophy behind it, right, that's a good question. I guess fundamentally needs will arise and needs will arise in an emergency operational environment at any time, we can't control that, or at least we find it very difficult to control those emergent properties of the environment which result in emergent needs".

Finally, when discussed the implications of a new requirement emerging from variability in use, a member of the engineering noted:

"... a new kind of threat that we hadn't had before...things like, I suppose, interchangeability, there may be some relaxation of things like that because we say, "Look, we understand that there may be complexities further down the stream

but this is to get round an immediate problem that we have to get round", so there are all those considerations".

This quote highlights the difficulties in efficiently integrating a design change when (1) it is a new functionality to deal with a new problem associated with variety in use i.e., the new threat and (2) the speed at which the design change is required by the customer in use.

The second point also highlights a second theme as a driver for complexity; urgency (speed). From the case data, we define urgency as the speed at which the customer requires the design change to be integrated. It was found that when the customer has a greater degree of urgency, further complexity in the product architecture and manufacturing supply chain would occur. In addition to the previous quote, the following extract from a field note with a member of the engineering team:

"We managed to implement the design changes the customer wanted, but the timescales they provided and the legacy fleets we work with meant they were not designed as we would like from a through life cost perspective. I expect the through life costs will be high. Evidence so far suggests they will be, but we do not have enough data as the campaigns were so recent".

This quote also provides anecdotal evidence that the complexity arising in the architecture following design change integration will lead to higher through life costs for the organisation. This finding is consistent with existing research that states higher coordination costs mean higher costs of design and production (Baldwin & Clark, 2000; Mikkola, 2006).

The third sub-theme that emerged as a driver for complexity was novelty of the design change. From the case data, we define novelty of the design change as how new the functionality is for the vehicle (product) it is to be integrated into. Simply, does the new functionality align well (or not) with the existing architecture. If it does not, it was identified as being novel and more difficult to integrate as it falls outside the boundaries of the existing architecture. Examples of this are captured with interview extracts presented above. For example, novelty of the design change is also captured within a previous quote that discusses water requirements in different contexts of use.

Following a discussion of design novelty, it was noted that it was difficult to integrate new designs as there was also little flexibility in the existing platforms and their interfaces. Whilst designed to be modular, it was found that through life flexibility was not necessarily a design criterion when the original specification was created. This was found to add to difficulties in integrating novel designs (i.e., those outside the architectural boundary) when they emerge from use variety. This is captured in the following quote:

"I think probably the major contributors, at the minute, is, as I say, we're working with a legacy fleet and the legacy fleets are where they are at. The chance to change some of those interfaces, within the life cycle of vehicles that's left, isn't going to happen".

By supplementing the analysis of the product architecture with in-depth interviews, the results presented three core reasons why complexity rose in the physical asset and the supply chain according to the platform champions. These were emergence, urgency and novelty of the design. The results suggested these vary in degree, as does the level of complexity they create. This explains why in figure 1 varying degrees of complexity is added by each design change, suggesting the complexity introduced is not uniform and is context dependent i.e., it is dependent on what the requirement is. These findings lead us to the following research propositions:

Research Proposition 2a: Drivers of complexity for the product architecture and manufacturing supply chains are

I. *emergence of requirements during customer use;*
II. *urgency of the desired change as demanded by the customer;*
III. *novelty of the desired change compared with the existing functionality specified in the design rules.*

Research Proposition 2b: The degree of complexity is dependent upon the cumulative effect of emergence, urgency and novelty.

4.2 Can additive manufacturing allow organisations to support products in use without increasing complexity of the physical product and its associated supply chains?

As the results of RQ1A and B show that servitization can increase complexity in the physical product and the supply chain for three main reasons; emergence, urgency and novelty of the design change, we can now address RQ2. The case organisation studied in this research is currently developing their AM strategy alongside their servitization strategy and provided a novel opportunity to gain insight into the use of AM within complex PSSs. A common theme throughout the analysis was the complimentary nature of AM in addressing some of the challenges traditional manufacturing faces. These include managing the complexity identified in the results of RQ1. One interviewee discussed how they are developing AM to allow components to be product agnostic as opposed to product specific, stating:

"... if you suddenly said, "Well, I'd like to put a mine plough on the front of this vehicle, I've got one here, what do I need? Oh well, if I do these… take these interfaces, let's print all of this and let's then mount that on there." ... so in a very short space of time you've gone from it not having that capability to suddenly, yes, I can now mount this and put it on".

In line with the discussion within the literature review, this quote highlights how component parts become product agnostic as opposed to being product specific. AM allows pre-defined interfaces that connect the component (e.g., mine plough) to the main platform (e.g., the vehicle) to be modified within the parameters defined within the software. Assuming no structural and functional parameters are violated in the modification, which are determined by the engineer prior to releasing the file, then mounting components from other design hierarchies is made possible by AM on an individual customer basis. This provides flexibility in the provision of interfaces at the point of use without sacrificing component integrity. However, a number of interviewees acknowledged other engineering criteria would need to be developed/adapted to successfully implement this capability within servitized supply chains supported by AM. The interviewee acknowledges the speed at which AM can produce components, showing that the technology reduces lead times and mitigates some of the complexity in existing manufacturing supply chains. Further evidence came from an engineer when discussing supply chain lead times and coordination:

"It's not just whether the current manufacturing approach is as fast, it is the end to end process around that part…If I want a spare part that's made as a cast part…what I've got to do is raise the order…they've then got to man up the foundry and there might be minimum order quantities, so they wait until they've got enough order to warrant running up the foundry so you've got, potentially, an indeterminate lead time… can AM help to increase operational flexibility, which, in turn, will help you respond better to an unidentified or emerging threat? Yes".

AM could be used to address or mitigate all three factors that currently create complexity in the physical product and the supply chain. First, AM allows the organisation to speed up their response to demand variation in use, addressing the complexity that is currently introduced by urgency. Interviewees discussed how traditional supply chains can deliver larger components which are less amenable to AM, whilst AM deployed closer to the customer can be used to manufacture novel interfaces that allow for greater interchangeability between different product platforms. The complimentary nature of AM reduces complexity during the integration of the parts into the products architecture (see table A1 in the appendices for further data supporting the benefits of AM for manufacturing supply chains). This is a result of AMs novel digital characteristics that support a higher degree of geometric freedom to create interfaces that may not have been possible with traditional manufacturing restricted by tooling, forming etc. The combination of AM into traditional manufacturing systems allows organisations to shift from a reactive approach to UORs to a proactive approach.

"Now as we move further forward into the future where we've expecting quite a lot of disruptive change, which has been driven by technology, we'll have to put much more flexibility, much more adaptability as well, into the designs of our future products in order to meet these changing requirements…the likelihood is there's going to be some hybrid model of the two [AM and traditional manufacturing] where you can produce products which are adaptable, which are flexible, and at the same time, can produce new products or even modify existing ones for a more UOR type approach".

Our results support Holmström & Partenan (2014) and provide empirical evidence that AM will lead to novel hybrid supply chain solutions that can support product adaption in use. This data provided here leads us to the following research proposition:

Research Proposition 3: Traditional manufacturing and additive manufacturing can be used in combination to overcome the challenges created by the drivers of complexity.

AM has been identified as a supply chain technology that facilitates the management of complexity that currently arises in product architecture and supply chain, but it is not a stand-alone supply chain solution. The research shows that AM is most beneficial for changes in smaller components that do not dramatically impact on other components or create changes outside of modules. This finding aligns with existing research around AM (e.g., Liu et al., 2013; Holmström & Partnenan., 2014; Li et al, 2016; Heinon & Hoberg, 2019) and modularity that discusses core (standard) and peripheral (variety) modules (Baldwin & Clark, 2000; Rajala et al, 2019).

5.0 Discussion

5.1 Theoretical implications

In responding to the call to investigate the design challenges for the physical product posed by Ng et al. (2009) and Smith et al. (2014), we find that high variety servitized contexts increase complexity in the products architecture. A number of factors were found to influence this including emergence, urgency, novelty of the design change and the restrictions of modularity theory when design changes are integrated using traditional manufacturing technology. We do not rule out the benefits of traditional modular designs and their ability to satisfy diverse customer needs, particularly where organisations are not exposed to and responsible for the customers' context of use. This traditional approach is suited to closed system contexts; product sales relationships where value is in exchange as opposed to service offerings where value is realised in use. We identify two contexts within which two different strategies are present; designing for low variety and designing for high variety. In designing for low variety, modularity is a suitable strategy for firms to adopt because the variety of use is predictable in advance of production and therefore post-production design changes that introduce complexity are unlikely to be needed (Green et al, 2017). In designing for high variety, modularity remains beneficial, but is inefficient as part of a traditional supply chain system that relies on traditional manufacturing technologies.

The research highlights the limitations of the normative assumptions made when conceptualising the product as having frozen design specifications before production (Ng, 2013; Henfriddson et al, 2014). The normative O&SCM assumption is the intangible service elements are adaptable emergent demand but the product is fixed/frozen and therefore is unchangeable (Smith et al, 2014; Green et al, 2017). Whilst modularity has helped organisations to 'adapt' the product prior to exchange, it fails to accommodate change at the point of use where variability in the customers' use of the offering changes the requirements of the product. This is because whilst modularity does allow products to be modified, it is most often within the functional boundaries defined early in the design cycle. Indeed, this is explicitly stated in modularity theory as it specifies a complete picture of the structural and functional elements of the architecture to be frozen prior to production (Baldwin & Clark, 2000). Drawing on both the literature review and the results of our study, our research suggest it is time to drop this normative assumption. As part of industry 4.0 information (big data), communication, digital design and additive manufacturing as a system allows us to capture emergent consumer need/demand and adapt the product to be an absorber of variety in a scalable fashion whilst continuing to control complexity (Ng, 2013; Holmström & Partenan, 2014; Schroeder et al, 2019). In finding these results, our work also supports Ng et al (2011) and Maglio et al. (2015) who suggest simple extensions of existing engineering, supply chain and operations models are not sufficient for services where reacting to user value in use leads to emergent demand and contextual variety. Case evidence shows that AM technology drawing on libraries of or rapidly creating new digital parts to which immediate design changes can be implemented meet emergent need. This creates a new AM modularity concept, removing the rigid specification of user requirement so early in the design cycle (Garud et al, 2008; Ng et al, 2009). Designs can be now be modified, within specific parameters determined by the engineering teams, or rapidly developed at the point of use to quickly respond to emergent need. It is important to note that the results suggest the former would be more amenable to larger components or modification of interface specs whilst the latter would be more amenable to smaller, non-safety critical components. Our results suggest researchers should reconsider their focus upon the intangible service elements (Green et al., 2017) and consider how AM as part of the system to make products able to absorb variety as part of a supply chain solution to emergent high variety. Core theoretical assumptions must change, moving away from viewing products as frozen structural and functional elements (Henfridsson et al, 2014) towards a new concept where the product is adaptive within the wider service system (Ng, 2013; Holmström & Partenan, 2014). We therefore contribute to the literature by providing evidence from our case study that this new system may not add to complexity from the three sources and that through the adoption of AM technologies it is possible to enhance product centric service systems such that the product itself suddenly becomes adaptive. In addition, we have contributed to the ongoing need for more empirical research surrounding operational design and delivery issues when transitioning from product to service (Oliva & Kallenberg, 2003; Smith et al, 2014). Notably, we offer a novel contribution exploring these challenges from the perspective of the physical asset and its supply chain, as opposed to the intangible service elements predominately covered within the existing literature.

5.2 Managerial Implications

This research has shown complexity is not only present in the intangible service elements of the organisations value proposition, but also the physical product and the supply chain under conditions of high variety. Specifically, we highlight how variability in the customers' use of the product has implications for the products architecture and the efficiency of the supply chain. Notably, evidence suggests the combination of existing modularity manufacturing theories and traditional manufacturing technologies are not suitable for all servitized contexts. Organisations need to examine and invest in new industry 4.0 technologies to capture emergent need and partly meet that need more quickly through AM. Organisations will need to address normative assumptions that products have fixed design attributes and cannot absorb variety. Designers and engineers need to recognise that in product centric services the physical product is able, and well placed to absorb variety in use. Advances in AM technology can help support the design of efficient and effective delivery systems that can modify, tailor and adapt the product in use. A number of challenges for integrating AM to support the adaption of equipment in use still exist. Higher levels of emergence, urgency and novelty of design change plays a significant role in the degree of complexity created for the firm in both their product architecture and their supply chains. If organisations are able to successfully design and integrate a suitable delivery system supported by AM, that would provide a new source of competitive advantage. Finally, the potential benefits of AM driven supply chains will have an impact on competitive advantage and the organisations ability to absorb variety in use. For example, AM enabled supply chain will allow for faster delivery of components into the customers' context. AM allow organisations to match variety with variety in a feasible, cost efficient yet individualised format, leveraging the benefits of AM technology. Our case evidence suggests that AM will both compliment and replace elements of traditional manufacturing in servitized contexts, providing greater resource flexibility and speed in resource provision.

The interviewees acknowledged some significant obstacles to overcome in the technical capabilities of AM. These obstacles, including material options and throughput rate of component parts, identified within the literature review, are not easy to overcome. Interviewees were aware of the progress being made in AM technology and had confidence that these obstacles will be overcome in the long term. It was recognised that further work is needed before servitized manufacturers can make significant changes to their product supply chains. In particular, the interviewees recognised a number of challenges within their industry. One that recurred was that of safety and how could the materials and quality assurance processes ensure the components printed via AM could match those from accepted traditional manufacturing practice. Operations managers seeking to develop AM delivery systems to support their products in use should collaborate with design engineers, production engineers and management colleagues, examine accepted quality practice and the related soft systems.

5. Limitations and future research

6.1 Limitations

There are a number of limitations that need to be acknowledged. First, this study is a single case. Whilst the findings provide insights, it is difficult to generalize the results beyond the case studied. Whilst the findings may be replicated across capital goods markets, we cannot say with a high degree of confidence that the results apply outside of this context. It is therefore necessary to verify the results in other industries to confirm their wider applicability. Second, whilst we are able to show conclusively that architectural complexity increases through life, the research is only able to anecdotally show this has implications for through life costs and trade-offs in operations and supply chain performance. Future studies should incorporate quantitative data that allows for the effect on through life costs and operations performance to be measured as it is anticipated that complexity will have a negative consequence on these if organisations continue to utilise traditional production and supply systems. Third, whilst research indicated support for the hypothesis that AM can overcome the challenges of increased complexity in the physical product, we were not able to evidence this over the long term in practice as the organisation is only just embarking on their journey toward the adoption of AM within their operations and supply chains.

6.2 Future Research

Whilst we have acknowledged the limitations of the research, they open up a number of opportunities for future research. Literature commonly transposes modularity theory developed in manufacturing domains into service domains (e.g., Voss & Hsuan, 2009), we have shown that this is not always possible, especially when organisations shift from relatively closed systems to more open systems (e.g., outcome based contracting). As we have only shown this in a single setting, future research should seek to replicate the research across multi-settings to test whether the findings are consistent across contexts.

Further research is needed to understand how different organisations can best configure their service delivery systems and supply chain processes to support such a value proposition in the context of industry 4.0, with particular attention paid to AM. Second, whilst we provide anecdotal evidence to support the notion that through life costs would increase as a result of the additional complexity created by functional design changes (UORs), future studies could integrate quantitative through life and operational performance data to show a relationship between architectural complexity and trade-offs in operational performance (i.e., cost). Fourth, whilst outside the scope of this research, it would be useful to explore the legal components of design changes within servitized contracts. For instance, can organisations contractually bind design changes to within modules to avoid increases in architectural complexity? Fifth, insights into the nature of the interactions within the DSMs would be beneficial i.e., the type of interactions (e.g., electrical, mechanical, information etc.) and the strength of coupling between modules. This would support a deeper understanding into architectural complexity when integrating design changes in servitized contexts. Within this study, the binary nature of the DSM data available meant that we were not able to draw any further insight beyond that presented in the results. Finally, this study has only covered the supply side of industry 4.0, AM. Existing literature shows research with a wider digital systems perspective, where AM is combined with other industry 4.0 technologies, is needed to optimise the whole. On the demand side, Maull et al (2015) highlighted that the Internet of Things (IoT) could provide data about use of the asset and subsequently close the loop between supply and demand in on demand (full pull) markets. Schroeder et al. (2019) recently identified product use data enabled by industry 4.0 as a key resource for organisations in the digital era. A number of authors have suggested that product use data could be used to understand the customers' context of use and therefore provide resources via AM when required (Ng, 2013; Holmström & Partenan, 2014; Maull et al, 2015). Within our research, UORs are currently customer driven, as only military customers have visibility of their context of use. This means providers are reactive as opposed to proactive in their delivery of functional design changes. A number of interviewees suggested that the provider organisation should have responsibility to proactively design and deliver functionality that satisfies use in order to support continued operational performance of the physical asset. To become more proactive providers would require visibility of use in context, which can be achieved via IoT technologies and data analytics (Ng et al, 2009; Smith et al, 2014; Maull et al, 2015; Parry et al, 2016; Green et al, 2017).

Whilst our study focussed on supply side AM , future studies will take the broader systems view requested by Maull et al (2015), integrating IoT demand signals with AM production to advance operations and supply chain management theory.

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Appendices

The following table presents examples of data supporting each theme. A number of quotes discuss traditional manufacturing and AM together as they were comparing, therefore some quotes are multifaceted and represent multiple themes. To avoid duplication, they are placed in a single box. Round 1 and round 2 refers to the stage of interviews, titles of employees have not been used to prevent identification against particular quotes.

Theme	Sub-theme	Data (example quotes)
Product Architecture	**Urgency**	[when comparing emergent requirements during wartime and peacetime]…"The difference is that if you identify a problem in training, you've have more time to think about it before having to act on it" – Round 2 "We managed to implement the design changes the customer wanted, but the timescales they provided and the legacy fleets we work with meant they were not designed as we would like from a through life cost perspective. I expect the through life costs will be high. Evidence so far suggests they will be, but we do not have enough data as the campaigns were so recent" – Round 2
	Emergence	[when discussing types of design change responding to emergent needs]…"One of the reasons most people like software based architecture now is that the software is more easily upgradeable than electronics" – Round 2 "We find it very difficult to control those emergent properties of the environment which result in emergent needs" – Round 2 "Storage is a big issue. It sounds trivial but in theatre they had a real problem with water, because they had to drink, what was it?...Something like that, so if you go out for any length of time, three or four day mission, suddenly you've got to store 60 litres of water on a vehicle for a crew of three or something like that, well where's that going to go? Well, we didn't plan that in the design because it wasn't a requirement" – Round 1 "The philosophy behind it, right, that's a good question. I guess fundamentally needs will arise and needs will arise in an emergency operational environment at any time, we can't control that, or at least we find it very difficult to control those emergent properties of the environment which result in emergent needs" – Round 2 "… a new kind of threat that we hadn't had before…things like, I suppose, interchangeability, there may be some relaxation of things like that because we say, "Look, we understand that there may be complexities further down the stream but this is to get round an

		immediate problem that we have to get round", so there are all those considerations" – Round 2 "Modularity enables you to be quicker. The cumulative effect of AM, in combination with a modular architecture, is probably greater than the sum of the parts because modularity will give you benefit, AM will give you benefit. Putting the two together, meaning you can quickly manufacture bespoke parts, to a particular threat, in a particular environment, on a particular vehicle, for a particular modular location, that's going to mean you're more agile" – Round 1
	Design Novelty	"So it's legacy platforms and stuff like that, so if we are support. Changing stuff is quite difficult and quite costly, quite timely". – Round 1 [when discussing difficulty in integrating novel design changes]… "Yes, I think legacy-wise it's just it tends to be cost prohibitive to retro-fit that to the fleet. So it's a big architectural change for all these vehicles". – Round 1 "I think probably the major contributors, at the minute, is, as I say, we're working with a legacy fleet and the legacy fleets are where they are at. The chance to change some of those interfaces, within the life cycle of vehicles that's left, isn't going to happen" – Round 1 "Now as we move further forward into the future where we've expecting quite a lot of disruptive change, which has been driven by technology, we'll have to put much more flexibility, much more adaptability as well, into the designs of our future products in order to meet these changing requirements…the likelihood is there's going to be some hybrid model of the two [AM and traditional manufacturing] where you can produce products which are adaptable, which are flexible, and at the same time, can produce new products or even modify existing ones for a more UOR type approach" – Round 2
Supply Chain Complexity	**Urgency**	"…you can physically print a component…and you can use it on a vehicle in 24 hours, it would normally take you six weeks, eight week at best to get one made. So if you're out in the theatre…and you need stuff now, you can have it now as opposed to waiting for it…so your costs and your efficiencies also improve" – Round 1 "…if something does fall over quite quickly, it's not we need a one-off, or we've got to…you know, you've got a whole supply chain to interact with…whereas if you've got the AM capability, if something falls over…you can get something very quickly" – Round 1 "…you can make any one part or any one of 100 parts it's a lot more flexible than having 10 of each different part sitting there on the shelf just in case you need one. So from the flexibility operationally it's brilliant" – Round 1

		“The ability to just get even basic structures quickly from a CAD design is, not only is it cheaper but it cuts out the time for someone having to interface with all those people [in the supply chain]” – Round 1 “One of the other benefits of AM is potentially build time because it could be significantly quicker to print a part of AM than to actually go through traditional manufacturing” – Round 2 “It’s not just whether the current manufacturing approach is as fast, it is the end to end process around that part…If I want a spare part that’s made as a cast part…what I’ve got to do is raise the order…they’ve then got to man up the foundry and there might be minimum order quantities, so they wait until they’ve got enough order to warrant running up the foundry so you’ve got, potentially, an indeterminate lead time… can AM help to increase operational flexibility, which, in turn, will help you respond better to an unidentified or emerging threat? Yes”. – Round 1
	Emergence	“The difference that you get is the flexibility in lead time and responsiveness, so can AM help to increase the operational flexibility, which, in turn, will help you respond better to an unidentified or emerging threat? Yes.” – Round 1 [When discussing responding to emergent requirements]…”You can personalise a fleet of vehicles for a specific operation” – Round 1 [When discussing AM responding to emergent requirements]…”Irrespective of what kind of warfare you’re looking at, yes it’s flexibility at the point of use. Full stop” – Round 2 “…a huge advantage to the customer from their point of view, being able to do that at very short turnaround time, without having to move vast amounts of equipment in…as I say, the theatre may change on a daily basis, rather than weeks and weeks between that”. – Round 1 “usually you get people co-located the best we can or at least if we can’t co-locate them every morning, down by the wagon usually, have a line side meeting…everyone knows what the key things are for that particular day and everyone works together as best they can to do that”. – Round 2.
	Design Novelty	“If you don’t hold the stock, you don’t have to buy as much. You can afford to have lots of different designs to do lots of different things that you can pick as and when” – Round 1 “… if you suddenly said, “Well, I’d like to put a mine plough on the front of this vehicle, I’ve got one here, what do I need? Oh well, if I do these… take these interfaces, let’s print all of this and let’s then mount that on there.” … so in a very short space of time you’ve gone

		from it not having that capability to suddenly, yes, I can now mount this and put it on". – Round 1 "Situations where you find, in a particular scenario, the tool is not ideal for the job and you want to modify it somehow…you could effectively print a slightly different tool to suit a particularly different situation that was not anticipated" – Round 2 [When discussing novel design changes]… "It definitely gives you a lot more confidence and a lot more…it reduces you interfaces to suppliers" – Round 1

Table (i). Themes and Sub Themes with Example Quotes.

References

Anderson, P. (1999), Applications of complexity theory to organizational science. *Organisation Science*, Vol. 10, pp, 216-232.

Baines, T.S., Lightfoot, H.W., Benedettini, O., Kay, J. (2009), The servitization of manufacturing: A review of literature and reflection on future challenges. *Journal of Manufacturing Technology Management*, Vol. 20 No. 5, pp.547–567.

Baines, T., and H. W. Lightfoot. (2013), Servitization of the manufacturing firm: Exploring the operations practices and technologies that deliver advanced services. *International Journal of Operations & Production Management*, Vol. 34 No. 1, pp. 2–35

Baldwin, C.Y. and Clark, K.B. (2000), *Design Rules*, MIT Press, Cambridge, MA.

Baldwin, C.Y. (2008), Where do transactions come from? Modularity, transactions and the boundaries of firms, *Industrial and Coporate Change*, Vol. 17 No. 1, pp. 155-195.

Batista, L., Davis-Poynter, S., Ng, I., Maull, R. (2017), Servitization through outcome-based contract? A systems perspective from the defence industry. *International Journal of Production Economics*, Vol. 192 (October), pp. 133-143.

Berman, B. (2012), 3-D printing: the new industrial revolution, *Business Horizons*, Vol. 55 (2), pp. 155-162.

Benbasat, I., Goldstein, D., Mead, M. (1987), The case research strategy in studies of information systems. *MIS Quarterly*, Vol. 11 No. 3, pp.369–386.

Ben-Daya, M., Hassini, E., & Bahroun, Z. (2017), Internet of things and supply chain management: a literature review, *International Journal of Production Research*.

Suntherland, S. (2019), Are you a robot?, *Bloomberg*, [ONLINE] Available at: https://www.bloomberg.com/opinion/articles/2019-04-12/3d-printing-is-set-to-revolutionize-aviation-for-ge-honeywell. [Accessed 23 October 2019].

Braun, V. & Clarke, V. (2006), Using thematic analysis in psychology, *Qualitative Research in Psychology*, Vol. 3 No. 2, pp. 77–101.

Browning, T.R. (2001), Applying the design structure matrix to system decomposition and integration problems: a review and new directions, *IEEE Transactions on Engineering Management*, Vol. 48 No. 3, pp. 292–306.

Bustinza, O.F., Bigdeli, A.Z., Baines, T., Elliot, C. (2015), Servitization and competitive advantage. *Research Technology Management*, Vol. 58 No. 5, pp.53–60.

Cenamor, J., Sjödin, D.R, & Parida, V. (2017), Adopting a platform approach in servitization: Leveraging the value of digitialisation, *International Journal of Production Economics,* Vol. 192 (October), pp. 54-65.

Deloitte Insights. 2019. Transforming the supply chain with additive manufacturing, *Deloitte Insights*. [ONLINE] Available at: https://www2.deloitte.com/us/en/insights/focus/3d-opportunity/additive-manufacturing-3d-printing-supply-chain-transformation.html. [Accessed 23 October 2019].

Eisenhardt, K.M. (1989), Building Theories from Case Study Research. *The Academy of Management Review*, Vol. 14 No. 4, pp.532–550

Eisenhardt, K. & Graebner, M. (2007), Theory building from cases: Opportunities and challenges. *Academy of Management Journal*, Vol. 50 No. 1, pp.25–32.

Eppinger, S. & Browning, T. (2012), *Design structure matrix methods and applications*, Cambridge: MIT Press.

Fixson, S.K. (2005), Product architecture assessment: A tool to link product, process and supply chain design decisions, *Journal of Operations Management*, Vol. 23 No 3–4, pp.345–369.

Garud, R., Jain, S., & Tuertscher, P. (2009), Incomplete by design and designing for incompleteness, *Organizational Studies*, Vol. 29 No 3, pp. 351-371.

Green, M., Davies, P., Ng, I. (2017), Two strands of servitization: A thematic analysis of traditional and customer co-created servitization and future research directions, *International Journal of Production Economics*, Vol. 192 (October), pp.40–53.

Grubic, T. (2014), Servitization and remote monitoring technology. A literature review and research agenda, *Journal of Manufacturing Technolology Management*, Vol. 25, pp. 100–124.

Grubic, T. (2018), Remote monitoring technology and servitization: Exploring the relationship. *Computers in Industry*, Vol. 100, pp. 148–158.

Godsiff, P. (2010), Service systems and requisite variety, *Service Science*, Vol. 2 No. 1–2, pp.92–101.

Godsiff, P., Maull, R., & Davies, P. (2018), Systems behaviour and implications for service-dominant logic, in Lusch, R., & Vargo, S. (Eds), Handbook of Service Dominant Logic, Sage, London.

GOV UK. (2019), CDE themed competition: additive manufacturing, [ONLINE] Available at: https://www.gov.uk/government/publications/cde-themed-competition-additive-manufacturing. [Accessed 31 October 2019].

Hayes, R. (2002), Challenges posed to operations management by the "new economy," *Production & Operations Management*, Vol. 11 No. 1, pp.21–32.

Henfridsson, O., Mathiassen, L., Svahn, F. (2014), Managing technological change in the digital age: The role of architectural frames, *Journal of Information Technology*, Vol. 29 No. 1, pp. 27–43.

Heinen, J.J., & Hoberg, K. (2019), Assessing the potential of additive manufacturing for the provision of spare parts, *Journal of Operations Management*, Vol. 65, pp. 810-826.

Hobday, M. (2000), The project based organisation: an ideal form for managing complex products and systems? *Research Policy*, Vol. 29, pp. 871–893.

Holmström, J., Partanen, J., Tuomi, J., Walter, M. (2010), Rapid manufacturing in the spare parts supply chain: Alternative approaches to capacity deployment, *Journal of Manufacturing Technology Management*, Vol. 21 No. 6, pp.687–697.

Holmström, K. & Partanen, J. (2014), Digital manufacturing-driven transformations of service supply chains for complex products, *Supply Chain Management: An International Journal*, Vol. 19 No. 4, pp. 421–430.

Holmström, J., Holweg, M., Khajavi, S. H., & Partanen, J. (2016), The direct digital manufacturing (r) evolution: Definition of a research agenda, *Operations Management Research*, Vol. *9 No.* 1–2, pp. 1–10.

Huang, Y., Leu, M.C., Mazumder, J., Donmez, A. (2015), Additive manufacturing: current state, future potential, gaps and needs, and recommendations, *Journal of Manufacturing Science and Engineering*, Vol. 137 No. 1.

Ihl, C. & Piller, F. (2016), 3D printing as driver of localized manufacturing: Expected benefits from producer and consumer perspectives. In J.-P. Ferdinand, U. Petschow, & S. Dickel, eds. *The Decentralized and Networked Future of Value Creation*. Cham: Springer International Publishing, pp. 179–204.

Johnson, M., Mena, C. (2008), Supply chain management for servitised products: a multi-industry case study. *International Journal of Production Economics*, Vol. 114 No. 1, pp. 27–39.

Khajavi, S., Partanen, J., & Holmström. (2014), Additive manufacturing in the spare parts supply chain, *Computers in Industry*, Vol. 65 No. 1, pp. 50-63.

Kimbell, L., 2011. Designing for service as one way of designing services. International Journal of Design, Vol. 5 No. 2, pp.41–52.

Langlois, R. & Cosgel, M. (1998), The organisation of consumption. In M. Bianchi, ed. *The active consumer: Novelty and surprise in consumer choice*. London: Routledge, pp. 107–121.

Lightfoot, H., Baines, T., Smart, P. (2013), The servitization of manufacturing: a systematic literature review of interdependent trend, *International Journal of Operations and Production Management*, Vol. 33 No. 11/12, pp. 1408–1434.

Li, Y., Jia, G., Cheng, Y., & Hu, Y. (2016), Additive manufacturing technology in spare parts supply chain: a comparative study, *International Journal of Production Research,* Vol. 55 No, 5, pp. 1498-1515.

Liu, P., Huang, S.H., Mokasdar, A., Zhou, H., & Hou, L. (2014), The impact of additive manufacturing in the aircraft spare parts supply chain: supply chain operation reference (scor) model based analysis, *Production Planning & Control*, Vol. 24, No13-14, pp. 1169-1181.

Lyly-Yrjanainen, J., Holmström, J., Johansson, M.I., Suomala, P. (2016), Effects of combining product-centric control and direct digital manufacturing: the case of preparing customized hose assembly kits, *Computers in Industry*, Vol. 82, pp. 82–94.

MacCormack, A., Verganti, R., Iansiti, M. (2001), Developing products on "internet time": The anatomy of a flexible development process, *Management Science*, Vol. 47 No. 1, pp.133–150.

Maglio, P., Kwan, S., Spohrer, J. (2015), Commentary—Toward a Research Agenda for Human-Centered Service System Innovation, *Service Science*, Vol. 7 No. 1, pp.1–10.

Maull, R., Godsiff, P., Mulligan, C. (2015), Transitioning to the pull economy: the case of the UK railways. In *48th Hawaii International Conference on System Sciences*. pp. 1285–1294.

Meredith, J. (1998), Building operations management theory through case and field research. *Journal of Operations Management*, Vol. 16 No. 4, pp.441–454.

Mikkola, J.H. (2003), Modularity, component outsourcing, and inter-firm learning, *R&D Management*, Vol. 33 No. 4, pp.439–454

Miles, M., Huberman, M., & Saldana, J. (2014), *Qualitative data analysis: A methods sourcebook*, Thousand Oaks: Sage Publications.

Neely, A. (2008), Exploring the financial consequences of the servitization of manufacturing, *Operations Management Research,* Vol. 1 No. 2, pp. 103-118.

Neely, A., Benedettini, O., Visnjic, I. (2011), The servitization of manufacturing: further evidence, *Proceedings of the European Operations Management Association Conference,* Cambridge, UK.

Ng, I. (2013), *Creating new markets in the digital economy*, Cambridge: Cambridge University Press.

Ng, I., Badinelli, R., Polese, F., Di Nauta, P., Löbler, H., & Halliday, S. (2012), S-D logic research directions and opportunities: The perspective of systems, complexity, and engineering. *Marketing Theory*, Vol. 12 No. 2, pp 213-217.

Ng, I. & Briscoe, G. (2012), Value, variety and viability: New business models for co-creation in outcome based contracts. *International Journal of Service Science, Management, Engineering, and Technology*, Vol. 3 No. 3, pp.26–48.

Oesterreich, T., & F. Teuteberg. (2016), Understanding the Implications of Digitization and Automation in the Context of Industry 4.0: A Triangulation Approach and Elements of a Research Agenda for the Construction Industry, *Computers in Industry*, Vol. 83, pp. 121–139.

Opresnk D, Taisch. (2015), The value of Big Data in servitization, *International Journal of Production Economics*, Vol. 165, pp. 174–184.

Parnaby, J. (1988), A systems approach to the implementation of JIT methodologies in Lucas Industries. *International Journal of Production Research,* Vol. 26 No. 3, pp. 483-492.

Parry, G., Brax, S., Maull, R., Ng, I. (2016), Visibility of consumer context improving reverse supply with Internet- of-Things data. *Supply Chain Management : An International Journal*, Vol. 21 No. 2, pp.228–244.

Petrick, I. & Simpson, T. (2013), Point of View: 3D Printing Disrupts Manufacturing: How Economies of One Create New Rules of Competition. *Research-Technology Management*, Vol. 56 No. 6, pp.12–16.

Pimmler, T. & Eppinger, S. (1994), Integration analysis of product decompositions. In *ASME Design Theory and Methodology Conference*. Minneapolis.

Rajala, R., Brax, Saara, Virtanen, A., & Salonen, A. (in press), The next phase in servitization: transforming integrated solutions into modular solutions, *International Journal of Operations and Production Management.*

Rymaszewska, A., Helo, P., & Gunasekaran., A. (2017), IoT Powered Servitization of Manufacturing – An Exploratory Case Study, *International Journal of Production Economics*, Vol.192, pp. 92–105.

Salonen, A. (2011), Service Transition Strategies of Industrial Manufacturers, *Industrial Marketing Management*, Vol. 40 No. 5, pp. 683–690.

Salonen, A., Rajala, R., & Virtanen, A. (2018), Leveraging the benefits of modularity in the provision of integrated solutions: A strategic learning perspective, *Industrial Marketing Management*, Vol. 68 (January), pp. 13-24.

Salvador, F. (2007), Toward a product system modularity construct: Literature review and reconceptualization, *IEEE Transactions on Engineering Management*, Vol. 54 No. 2, pp.219–240.

Schilling, M. A. (2000), Toward a general modular systems theory and its application to interfirm product modularity, *Academy of Management Review*, Vol. 25 No.1, pp. 312–334.

Schroeder, A., Bigdeli, A., Galera Zarcos, C., & Baines, T. (2019) Capturing the benefits of industry 4.0: a business network perspective, *Production Planning and Control*, pp 1-17.

Simon, H. (1996), *The sciences of the artificial*, Cambridge: MIT Press.

Smith, L., Maull, R., Ng, I. (2014). Servitization and operations management: A service-dominant logic approach. *International Journal of Operations & Production Management*, Vol. 34 No. 2, pp.242–269.

Spring, M. & Araujo, L. (2017), Product biographies in servitization and the circular economy. *Industrial Marketing Management*, Vol. 60, pp.126–137.

Srai, J.S., Kumar, M., Graham., Phillips, W., Tooze, J., Ford, S., Beecher, P., Raj, B., Gregory, M., Tiwari, M.K., Ravi, B., Neely, A., Shankar, R., Charnley, F., & Tiwari, A. (2016), Distributed manufacturing: scope, challenges and opportunities, *International Journal of Production Research*, Vol. 53 No. 23, pp. 6917-6935.

Tziantopoulos, K., Tsolakis, N., Vlachos, D. & Tsironis, L. (2019), Supply chain reconfiguration opportunities arising from additive manufacturing technologies in the digital era, *Production Planning & Control*, Vol. 30 No. 7, pp. 510-521.

Ulrich, K. (1995), The role of product architecture in the manufacturing firm, *Research Policy,* Vol. 24 No. 3, pp. 419-440.

Verganti, R. & Buganza, T. (2005), Design inertia: Designing for life-cycle flexibility in internet-based services. *Journal of Product Innovation Management*, Vol. 22 No. 3, pp.223–237.

Vendrell-Herrero, F., O. F. Bustinza, G. Parry, and N. Georgantzis. (2016), Servitization, Digitization and Supply Chain Interdependency, *Industrial Marketing Management,* Vol. 60, pp. 69–8.

Vickery, S.K., Koufteros, X., Dröge, C., & Calantone, R. (2015), Product modularity, process modularity, a new product introduction performance: does complexity matter? *Production and Operations Management,* Vol. 24 No. 4, pp. 751-770.

Visnjic, I., Jovanovic, M., Neely, A., & Engwall, M. (2017), What brings the value to outcome-based contract providers? Value drivers in outcome business models. International Journal of Production Economics, Vol. 192, pp. 169–181.

Voss, C. A., & Hsuan, J. (2009), Service Architecture and Modularity. *Decision Sciences*, Vol. 40 No. 3, pp. 541-569.

Weller, C., Kleer, R., Piller, F.T. (2015), Economic implications of 3D printing. Market struc-ture models in light of additive manufacturing revisited, *International Journal of Production Economics.* Vol. 164, pp. 43–56.

Walther, G. (2015), Printing Insecurity? The security implications of 3D-printing of weapons, *Science and Engineering Ethics*, Vol. 21 No. 6, pp. 1435-1445.

Xu, L., Xu, L., & Li., L. (2018), Industry 4.0: state of the art and future trends, *International Journal of Production Research*, Vol.56 No.8, pp. 2941-296.

Yin, R. (2003), *Case study research: design and methods*, Thousand Oaks: Sage Publications.

Yoo, Y. (2013), The tables have turned: how can the information systems field contribute to technology and innovation management research? *Journal of the Association for Information Systems*, Vol. 14 No. 5, pp.227–236.

Yoo, Y. & Euchner, J. (2015), Design in the generative economy. *Research-Technology Management*, Vol. 58 No. 2, pp. 13-19.